Astrobiology Roadmap

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Introduction

Astrobiology is the study of life in the universe. It provides a biological perspective to many areas of NASA research, linking such endeavors as the search for habitable planets, exploration missions to Mars and Europa, efforts to understand the origin of life, and planning for the future of life beyond Earth.

The NASA Astrobiology Roadmap is the product of efforts by more than 150 scientists and technologists, spanning a broad range of disciplines. More than 100 of these participated in a three-day Roadmap Workshop held in July 1998 at NASA Ames Research Center, while others attended previous topical workshops and are participating by email. The co-chairs of the Roadmap team are David Morrison, Director of Space at NASA Ames Research Center, and Michael Meyer, Astrobiology Discipline Scientist at NASA Headquarters and Program Scientist for Mars Sample Return. The Roadmap participants include NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the still wider community who have no formal association with NASA.

Astrobiology addresses three basic questions, which have been asked in some form for generations. Astrobiology is exciting today because we have the technology to begin to answer these fundamental questions:

How does life begin and develop?

Does life exist elsewhere in the universe?

What is life's future on Earth and beyond?

The NASA Astrobiology Roadmap will provide guidance for research and technology development across several NASA Enterprises: Space Science, Earth Science, and the Human Exploration and Development of Space. The Roadmap is formulated in terms of ten Science Goals, and 17 more specific Science Objectives, which will be translated into specific programs and integrated with NASA strategic planning. In addition, the NASA Roadmap emphasizes four Principles that are integral to the operation of the Astrobiology Program.

Goals

In order to answer the fundamental questions of astrobiology, the NASA Astrobiology program purses the following science goals:

Question: How Does Life Begin and Develop?

Goal 1: Understand how life arose on the Earth.

Goal 2: Determine the general principles governing the organization of matter into living systems.

Goal 3: Explore how life evolves on the molecular, organism, and ecosystem levels.

Goal 4: Determine how the terrestrial biosphere has co-evolved with the Earth.

Question: Does Life Exist Elsewhere in the Universe?

Goal 5: Establish limits for life in environments that provide analogues for conditions on other worlds.

Goal 6: Determine what makes a planet habitable and how common these worlds are in the universe.

Goal 7: Determine how to recognize the signature of life on other worlds.

Goal 8: Determine whether there is (or once was) life elsewhere in our solar system, particularly on Mars and Europa.

Question: What is Life's Future on Earth and Beyond?

Goal 9: Determine how ecosystems respond to environmental change on time-scales relevant to human life on Earth.

Goal 10: Understand the response of terrestrial life to conditions in space or on other planets.

Question: How Does Life Begin and Develop?

Goal 1: Understand How Life Arose on Earth

Perform historical, observational, and experimental investigations to understand the origin of life on our planet, including the possibility that it arrived at Earth from elsewhere.

Terrestrial life is the only form of life that we know, and it appears to have arisen from a common ancestor. How and where did this remarkable event occur? We can now perform historical, observational, and experimental investigations to understand the origin of life on our planet. We should determine the source of the raw materials of life, either produced on this planet or arriving from space. We should seek to understand in what environments the components may have assembled and what forces led to the development of systems capable of deriving energy from their surroundings and manufacturing copies of themselves. We should also investigate the exchange of biological materials between planets to assess the possibility that life formed elsewhere and subsequently migrated to Earth.

Background

For the prebiotic Earth, we seek to understand the origin and chemical nature of organic and inorganic compounds, and the energy sources and micro-environments that created the context for the origin of life. Given a plausible primary source of organic components, alternative pathways by which such prebiotic compounds formed the ancient counterparts of proteins, nucleic acids, and lipid-like molecules can be investigated within plausible constraints. One major objective is to construct laboratory models of assemblies of biopolymers recognizable as protocells. These will then be used to create models for the first microorganisms able to replicate and evolve on the early Earth, thereby leading to a common ancestry that is consistent with the later development of biological diversity. Another approach is to use the phylogenetic and geologic record to point to characteristics of our earliest ancestor. We should also consider the possibility that life formed elsewhere and was seeded onto the developing Earth; if so, we can ask under what conditions elsewhere life might have arisen and been transported to our planet. Understanding the interplanetary transportation and survivability of organisms is also relevant to issues surrounding possible contemporary exchange of biological material with Mars and hence the importance of quarantine of Mars samples returned to Earth. Theoretical calculation of mass transport rates, life on Earth in extreme environments (Goal 5), and further study of meteorites and collections of interstellar materials should allow significant progress in understanding whether these natural processes provide a mechanism for spreading life through the universe. This research is closely related to the issue of planetary habitability (Goal 6) and the general issue of the life principle (Goal 2).

Question: How Does Life Begin and Develop?

Goal 2: Determine the General Principles Governing the Organization of Matter into Living Systems

Use laboratory and computational approaches to establish the general physical and chemical principles that lead to the emergence of living systems under different conditions in the universe.

To understand the full potential of life in the universe we must establish the general physical and chemical principles that lead to the emergence of systems capable of converting molecules for energy and growth (catalysis), generating offspring (reproduction), and changing as conditions warrant (evolution). Terrestrial life is based on the chemistry of carbon moderated by liquid water. Such organic chemistry is common throughout the cosmos. But are terrestrial biochemistry and molecular biology the only such phenomena that can support life? Having only one example, we do not know which properties of life are general and necessary, and which are the result of specific circumstances or historical accident. We seek these answers by pursuing laboratory experimental approaches and computational theoretical approaches.

Background

The molecular machinery leading to the origin of life on other planets might well be substantially different from the one that formed on the early Earth because the remarkable versatility of organic chemistry offers multiple solutions for the basic requirements of life. Life on Earth represents only one example of living systems. One genetic code, one set of amino acids of specific chirality, and one energy currency have survived from primitive Earth. To understand the full potential of life in the universe it is necessary to go beyond our specific example and establish the general physical and chemical principles that lead to the emergence of the primary attributes of the living state: auto-catalysis, self-organization, spatial containment of functions, reproduction and evolution. This can be done by combining experimental and theoretical (computational) approaches, in which the fundamental principles governing biological organization of matter can be tested by constructing new biomimetic systems that possess the main attributes of a living state. This research is in effect a generalization of the origin of terrestrial life (Goal 1) and is related directly to the question of life on other worlds (Goal 6, Goal 7, and Goal 8).

Question: How Does Life Begin and Develop?

Goal 3: Explore How Life Evolves on the Molecular, Organism, and Ecosystem Levels

Utilize modern genetic studies, the fossil record, and ecosystem analyses to understand the processes of evolution, with emphasis on the development of microbial communities.

Life is a dynamic process of changes in energy and composition that occurs at all levels of assemblage, from the molecular level to ecosystem interactions. Much of traditional research on evolution has focused on organisms and their lineages as preserved in the fossil record. However, processes such as the exchange of genetic information between organisms and changes within DNA and RNA are key drivers of evolutionary innovation. Modern genetic analysis, using novel laboratory and computational methods, allows new insights into the diversity of life and evolution at all levels. Complementary to such studies are investigations of the evolution of ecosystems consisting of many interdependent species, especially microbial communities.

Background

The powerful techniques of molecular biology and molecular phylogenetics are revolutionizing our understanding of the diversity of life and the relationships between organisms. Studies of RNA and other conserved gene sequences have revealed previously unknown kingdoms of organisms in unlikely habitats, and have led to new hypotheses about environmental conditions for the origins of life. However, an understanding of the evolution of primary lineages requires more detailed studies at the genome level. Indeed, initial studies indicate that, early in evolution, transfers of genes between organisms may have been common. Coupled with mechanisms such as gene duplication and gene rearrangement, these processes indicate that simple mutation and selection are not the only evolutionary drivers. Studies of individual gene families must be extended to previously undescribed microbial species. New research teams and methodologies are needed to develop and process genome data from key taxa. If gene transfer is indeed an ancient process, it will be important to determine when and how key functions arose and spread in genomic consortia. This effort will allow reconstruction of the development of genomic complexity. Coordinated studies of microbial diversity and of changes in microbial communities are required in order to identify genetic and environmental factors that influenced the spread of biological diversity and its influence upon biospheric change. For example, we must understand how organisms affect each other, and how ecosystems alter the environment through modulation of chemistry and the composition of the oceans and atmosphere. The study of Earth's global ecology is being transformed by new technology (remote sensing and geographic information systems), process-oriented and interactive system modeling, as well as new paradigms for thinking about the global ecosystem. Our understanding of evolution will also be altered by considering catastrophic environmental changes of external origin, including asteroid and comet impacts and the consequences of nearby stellar explosions. This research is linked to studies of the co-evolution of life and the planet (Goal 4), the ability of life to survive in extreme environments (Goal 5), and the search for biomarkers on distant planets (Goal 7).

Question: How Does Life Begin and Develop?

Goal 4: Determine How the Terrestrial Biosphere has Co-Evolved with the Earth

Trace the coupled evolution of life and the planet by integrating evidence acquired from molecular biology, studies of present and historical environments, and research in ecology and organismal biology.

Just as life evolves in response to changing environments, changing ecosystems alter the environment of Earth. Scientists can trace the co-evolution of life and the planet by integrating evidence acquired from studies of current and historical molecular biology (genomics) with studies of present and historical environments and organismal biology. We seek to understand the diversity and distribution of our ancient ancestors by developing increasingly sensitive technology to read the record of life as captured in biomolecules and in rocks (fossils), to identify specific chemical interactions between the living components of the Earth (its biosphere) and other planetary subsystems, and to trace the history of Earth's changing environment in response to external driving forces and to biological modifications.

Background

We need to use the geologic record to attach dates and environmental context to evolutionary events, leading to a robust history of the biosphere, based on biomolecular, paleoenvironmental, and paleobiological evidence. Further, by examining the history of life in an environmental context and by studying the evolution of biochemical pathways that yield preservable records (biominerals, accumulations of trace elements, organic molecules, characteristic fractionations of stable isotopes, etc.), we can begin to reconstruct the mechanisms that link environmental and biological changes. Research on these biochemical pathways will also create an inventory of bio-indicators that may be sought in ancient rocks on Earth and on other planets. Specific chemical interactions between the biosphere and its host planet, and their role as evolutionary drivers, will be illuminated by studies of biogeochemical cycles and significant biological byproducts, such as molecular oxygen. The development of Earth's atmosphere will thus be understood in much greater detail, with a new and more fundamental view of factors controlling its levels of oxygen and carbon dioxide. Another outcome will be a better understanding of the evolution of Earth's biosphere. Paleontological evidence for the first appearances of novel kinds of organisms will be integrated with molecular phylogenies using quantitative approaches to the fossil record and precise geochronology. Understanding the full diversity of our evolving biosphere requires that the fossil records of extreme environments be explored and documented, an exercise that also has relevance for the search for life on other worlds. All of this research requires a deeper understanding of evolutionary mechanisms at the levels of molecules, organisms and ecosystems, as discussed under Goal 3. The results contribute directly to the identification of biomarkers (Goal 7).

Question: Does Life Exist Elsewhere in the Universe?

Goal 5: Establish Limits for Life in Environments That Provide Analogues for Conditions on Other Worlds

Investigate the adaptation of life to the full range of habitable environments on our own planet, past and present, and use these as analogues for conditions on other bodies in our solar system, such as Mars or Europa.

Life is found on the Earth anywhere liquid water is present, including such extreme environments as the interior of nuclear reactors, ice-covered Antarctic lakes, suboceanic hydrothermal vents, and deep subsurface rocks. To understand the possible environments for life on other worlds, we must investigate the full range of habitable environments on our own planet, both today and in the past. We will investigate these extreme environments not only for what they can tell us about the adaptability of life on this planet, but also as analogues for conditions on other bodies in our solar system, such as Mars or Europa.

Background

To understand the potential for life on other worlds, we should begin by investigating the limits to life on our own planet. The tolerance for extreme conditions shown by terrestrial life is much broader than previously thought. Recent research on some of the Earth's smallest inhabitants has shown them to be remarkably versatile in their choice of lifestyles, with communities of microorganisms thriving in such extreme environments as nuclear reactors, perennially ice-covered Antarctic lakes, the interiors of rocks, hydrothermal springs and deep subsurface aquifers. Some extreme environments, such as those near marine hydrothermal vents, have actually been suggested as possible sites for the origin of life on Earth. Investigation of extremophile organisms and their habitats provide first-order scientific return in their own right (e.g., adaptive mechanisms, origin and evolution of life) as well as analogue environments for Mars and Europa exploration (Goal 8). It is also of interest to identify terrestrial environments that do not support life, such as glacial ice fields, and to ask why life has not adapted to fill all environmental niches that are energetically possible. Such studies can also assist in identifying the chemical or morphological signatures of life in environments that differ significantly from that of the bulk of the Earth's surface (Goal 7).

Question: Does Life Exist Elsewhere in the Universe?

Goal 6: Determine What Makes a Planet Habitable and How Common These Worlds Are in the Universe

Investigate how planets acquire and sustain liquid water, and use theoretical and observational studies of the processes of planet formation as well as surveys of a representative sample of planetary systems to locate possible abodes for life.

Where should we look for extraterrestrial life? Based on our only example (life on Earth), liquid water is a requirement. We must therefore determine what sort of planets are likely to have liquid water and how common they might be. Understanding the origin of water on our own planet and other member of the solar system will yield insights on the ways water might be distributed within an emerging planetary system, and research on climate changes in response to solar variability will investigate the long-term stability of habitability on a planet. Studying the processes of planet formation and surveying a representative sample of planetary systems will determine what planets are present and how they are distributed, essential knowledge for judging the frequency of habitable planets.

Background

The abundance of planets with habitable environments is critical for understanding the role of life in the universe. The formation of planets, and the resulting configuration of planetary systems, can be approached both empirically and theoretically. In order to understand fully the process of planet formation, especially as it relates to planetary habitability, our current observational data base must be expanded to include higher spatial and spectral resolution studies of protoplanetary disks, detection and study of extra-solar planetary systems (down to and including Earth-sized planets), and distribution and properties of small bodies and dust in the solar system. From our only known example of life, we conclude that habitability depends on the existence and long term stability of liquid water in which nutrient and waste transport can occur and catalytic function and exchange of genetic material are possible. There must also be a source of energy that maintains the system away from the equilibrium state. Since all life with which we are familiar requires liquid water during at least some stage of its life cycle, the criteria for habitability should begin with the need for liquid water. Even with this limitation, there are many questions to be answered in order to understand where life might originate and thrive. Was Earth's water included in the original planetesimals from which Earth formed, or added later by impacts of asteroids or comets? Given the changes in the Sun's brightness over the past 4.5 billion years, how was water maintained as a liquid throughout most of Earth's history? As a starting point, the habitable zone in any planetary system is most simply defined as the region where liquid water is stable on a planet's surface, which depends on the type of star and the planet's orbit (and may even be possible on a satellite around another planet). The frequency of occurrence of planets in habitable regions around other stars be answered empirically, by surveying a representative sample of planetary systems (including Earth-mass planets) and determining their configuration. Understanding the stability of climate is related to Goal 4, while establishing the limits of habitability relates directly to Goal 5 and Goal 8.

Question: Does Life Exist Elsewhere in the Universe?

Goal 7: Determine How to Recognize the Signature of Life on Other Worlds

Learn to recognize extraterrestrial biospheres, by identifying structural fossils or chemical traces of extinct life in returned samples and by investigating what biomarkers could be detected in the spectra of planets circling other stars.

We are poised on the brink of searching for life, past or present, on a variety of worlds. This search requires that we be able to recognize extraterrestrial biospheres and to detect the signatures of extraterrestrial life. Within our own solar system, and based on our experiences here on Earth, we must learn to recognize structural fossils or chemical traces of extinct life that may be found in extraterrestrial rocks or other samples. To understand remotely sensed information from planets circling other stars, we should develop a catalog of possible signatures of life.

Background

Today, with recent discoveries of extrasolar planets and of possible evidence for past life on Mars, the age-old question "Are we alone?" is once again in the forefront of scientific inquiry. Our search for life beyond Earth requires an ability to recognize the potential for extraterrestrial biospheres and a capacity to detect the signatures of extraterrestrial life. Within our own solar system, we must learn to recognize the fossils or other biomarkers of extinct life that may be found in returned samples. It is also essential to learn to identify the chemical signatures of life on a distant world through remote sensing of its atmosphere or surface. On Earth, life has produced easily detectable atmospheric and surface changes. These changes include high concentrations of 02 and 03 in the atmosphere and the presence of a distinctive spectral feature (due to chlorophyll) on the surface. However, these effects have been most pronounced only for the last billion years of Earth history. For the previous several billion years during which Earth had life, the atmospheric and surface signatures are not fully understood. In exploring other worlds, it is critical that we generalize the process of coevolution of planet and life (Goal 3 and Goal 4). A long-term consideration is to develop alternative methods of searching for life, such as detecting radio signals or other artifacts from an advanced civilization.

Question: Does Life Exist Elsewhere in the Universe?

Goal 8: Determine whether There Is (or Once Was) Life Elsewhere in Our Solar System, Particularly on Mars and Europa

Explore the solar system from a biological perspective, emphasizing the search for past or present life on Mars and Europa, the two places beyond Earth that we know once supported liquid water.

Exciting data have presented us with the possibility that at least two other worlds in our solar system have (or have had) liquid water present. On Mars, there is evidence for stable flowing water early in that planet's history. Both in situ investigations and the analysis of returned samples will be necessary to understand Mars' historical climates and its potential for life. Extensive exploration of the martian surface will be required to evaluate the total potential for life on that planet, both past and present. Furthermore, exploration of the subsurface probably offers the only credible opportunity to find extant life on either Mars or Europa. Other planetary missions may identify additional sites of biological potential in our solar system.

Background

Beyond the Earth, the two worlds in our solar system that the are most likely to have, or have had, liquid water are Mars and Europa. The presence of liquid water, together with suitable energy sources, appears to be a requirement for life as we know it. On Mars there is evidence for stable flowing water early in that planet's history. Sedimentary deposits from possible paleolakes could hold fossil evidence of life that might have existed during this early wet period. Subsurface hydrothermal systems may persist on Mars today and are a possible target for a search for extant life. Both in situ investigations and the analysis of returned samples will be necessary to understand the past climate of Mars and its potential for life. In both cases, the selection of promising landing sites and identification of samples of biological significance are key. Europa is another planetary body, which probably has liquid water. If the presence of liquid water is confirmed, we will still need to address the history of these global oceans, to know whether they have persisted over geological time. Access to suitably selected europan surface samples may provide information on the contents of the water. On longer time-scales, deep penetration of the ice layer could provide a direct sample of the europan ocean and lead to remote submersible vehicles instrumented to search for evidence of marine life. Access to the deep subsurface of both Mars and Europa will required autonomous drilling technologies to provide the primary potential for discovery of extant alien life in our solar system. Understanding where to search and how to identify evidence for life are directly related to Goal 5, Goal 6, and Goal 7.

Question: What is Life's Future on Earth and Beyond?

Goal 9: Determine How Ecosystems Respond to Environmental Change on Time-Scales Relevant to Human Life on Earth

Examine the habitability of our planet over time in the face of both natural and human-induced environmental changes, and assess the role of rapid changes to enable predictive models of environment-ecosystem interaction.

Human-induced changes on Earth -- including contamination of oceans, freshwater and soil; deforestation and desertification; exotic species invasion; ozone depletion in the stratosphere; changes in atmospheric C02 levels, and the potential for sea level rise -- are altering the adaptation and evolution of our biosphere. Research at the level of the whole biosphere is needed to examine the habitability of our planet over time in the face of both natural and human-induced environmental changes. To help assure the continuing health of this planet and to understand the potential long-term habitability for other planets we need to assess the role of rapid changes in the environment and develop our knowledge base to enable predictive models of environment-ecosystem interaction.

Background

Astrobiology will seek to understand and to predict how changes on Earth have and will alter the adaptation and evolution of our biosphere on time scales measured in units of one million years to less than one year. Rapid environmental changes on Earth associated with recent human activities include toxic contamination of oceans, freshwater and soil, deforestation and desertification, exotic species invasion, decline in ozone in the stratosphere, and large changes in atmospheric C02. To help assure the habitability of a planet for humans, we will need to develop experimental methods to detect critical biophysical and geochemical components and their interactions during the formation of new ecosystems. It will be necessary also to integrate experimental results by development of models and theory that can address indirect effects and nonlinear environmental interactions that could produce unexpected and counter-intuitive impacts on the human biosphere. This integrated research approach will seek ultimately to identify the consequences for habitability of Earth if environmental changes outpace the capacity for adaptation and evolution of natural ecosystem components. Ultimately we desire to understand a range of conditions that applies to other planets as well as the Earth, including planets that are both young and old, biologically more simple or more complex than present-day Earth. We should attempt to broaden our perspective of the planet over time to investigate the spectrum of biosphere development. Biosphere-level research is needed to define the general habitability a planet and mechanisms of bioprotection, mainly through study of the interactions of Earth's ecosystems with its atmospheric chemistry and radiation balance. This research is a natural extension of Goal

3 and Goal 4 into current times, moving from historical studies into direct observation and experiment dealing with rapid rates of change.

Question: Does Life Exist Elsewhere in the Universe?

Goal 10: Understand the Response of Terrestrial Life to Conditions in Space or on Other Planets

Study the adaptation and evolution of Earth life in other environments, including the Space Station and Mars, and investigate the possibility of bioengineering ecosystems for better adaptation to alien environments.

All life that we know (that is, terrestrial life) has developed in a one-gravity field, protected by the Earth's atmosphere and magnetic fields. What happens when terrestrial life is moved off its home planet and into space or to the Moon or Mars, where the environment is very different from that of Earth? Can organisms and ecosystems adapt to a completely novel environment and live successfully over multiple generations? Are alternative strategies practical, such as bioengineering organisms for specific environments? The results from attempting to answer such questions will determine whether life is strictly a planetary phenomenon or can expand its evolutionary trajectory beyond its place of origin.

Background

All life that we know evolved on Earth. Now, for the first time in human history, we have the capability to intentionally move life beyond our home planet. Organisms have been carried to other surfaces in our solar system and have survived; yet they have not proliferated there. Environmental conditions on other planets provide potentially insurmountable challenges for evolution of terrestrial organisms. Delineating the mechanisms that organisms use to adapt to environmental extremes on Earth or simulated environments for other planets will provide insights into the environmental envelope that allows life to exist. The critical near-term questions to be answered are whether (and what kinds of) organisms live reproductively successful lives over multiple generations beyond Earth, and what genotypic changes (changes in the genes or DNA sequence) and phenotypic changes (changes appearance or physiology) result. The International Space Station will provide a testbed for studying evolution and ecological interactions of organisms. These studies will determine if simple organisms and their ecosystems evolve.

Objectives

Question: How Does Life Begin and Develop?

Sources of Organics on Earth

Objective 1: Determine whether the atmosphere of the early Earth, hydrothermal systems or exogenous matter were significant sources of organic matter.

Origin of Life's Cellular Components

Objective 2: Develop and test plausible pathways by which ancient counterparts of membrane systems, proteins and nucleic acids were synthesized from simpler precursors and assembled into protocells.

Models for Life

Objective 3: Replicating, catalytic systems capable of evolution, and construct laboratory models of metabolism in primitive living systems.

Genomic Clues to Evolution

Objective 4: Expand and interpret the genomic database of a select group of key microorganisms in order to reveal the history and dynamics of evolution.

Linking Planetary and Biological Evolution

Objective 5: Describe the sequences of causes and effects associated with the development of Earth's early biosphere and the global environment.

Microbial Ecology

Objective 6: Define how ecophysiological processes structure microbial communities, influence their adaptation and evolution, and affect their detection on other planets.

Question: Does Life Exist Elsewhere in the Universe?

The Extremes of Life

Objective 7: Identify the environmental limits for life by examining biological adaptations to extremes in environmental conditions.

Past and Present Life on Mars

Objective 8: Search for evidence of ancient climates, extinct life and potential habitats for extant life on Mars.

Life's Precursors and Habitats in the Outer Solar System

Objective 9: Determine the presence of life's chemical precursors and potential habitats for life in the outer solar system.

Natural Migration of Life

Objective 10: Understand the natural processes by which life can migrate from one world to another. Are we alone in the Universe?

Origin of Habitable Planets

Objective 11: Determine (theoretically and empirically) the ultimate outcome of the planet-forming process around other stars, especially the habitable ones.

Effects of Climate and Geology on Habitability

Objective 12: Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help define the frequency of habitable planets in the universe.

Extrasolar Biomarkers

Objective 13: Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extrasolar planet.

Question: What is Life's Future on Earth and Beyond?

Ecosystem Response to Rapid Environmental Change

Objective 14: Determine the resilience of local and global ecosystems through their response to natural and human-induced disturbances.

Earth's Future Habitability

Objective 15: Model the future habitability of Earth by examining the interactions between the biosphere and the chemistry and radiation balance of the atmosphere.

Bringing Life with Us beyond Earth

Objective 16: Understand the human-directed processes by which life can migrate from one world to another.

Planetary Protection

Objective 17: Refine planetary protection guidelines and develop protection technology for human and robotic missions.

Question: How Does Life Begin and Develop?

Sources of Organics on Earth

Objective 1: Determine whether the atmosphere of the early Earth, hydrothermal systems or exogenous matter were significant sources of organic matter.

Determining the primary sources and nature of organic matter from which living systems emerged on the prebiotic Earth is still a controversial endeavor. The key proposed sources include synthesis in the atmosphere of the early Earth; synthesis in warm hydrothermal systems or in geothermal subsurface environments; delivery to the early Earth by comets, meteorites and microscopic, interplanetary dust particles; or some combination of these possibilities. Each hypothesis leads to different predictions about the composition and availability of organic starting material and the nature of the earliest pre-metabolic processes leading to the origin of life. We must, therefore, determine the relative contributions of each of these sources of organic material to life's origins on the primitive Earth, and define and characterize those mechanisms that allowed adequate concentrations of these chemicals for the necessary interactions and reactions to occur.

Implementation

Near- to Mid-Term

Using space missions and infrared telescopes, explore how organics, initially synthesized in the interstellar dust cloud from which the Solar System was formed, are chemically altered before they are delivered to earth. This research will help to determine the chemical structure and composition of exogenous organic compounds and the extent to which they contributed to the inventory of prebiotic organics on earth. This task will benefit from missions to analyze organic material in both interplanetary dust particles as well as meteor showers. In addition, ground, air (SOFIA) and space-based (SIRTF) observatories will provide key data.

Conduct realistic laboratory simulations of chemical reactions under the conditions existing on planetary bodies, on the surface of the primitive earth and in hydrothermal vents. Investigate the potential of the synthesized compounds to contribute to the formation of biological structures.

Perform computer modeling of prebiotic chemical synthesis in different environments taking into account appropriate external constraints, such as energetics, temperature, pressure, and surface catalysis potential.

Examine the geological record for evidence of environmental conditions on the early earth. Examine ancient rock formations for the signature of early life in the form of microfossils, isotope ratios and mineral assemblages, and obtain evidence for the redox state of the earth mantle near the time of the origin of life. A reducing mantle was essential to maintain a reducing atmosphere on the prebiotic earth.

Study natural environments (e.g., hydrothermal vents) as models for primordial chemistry.

Future Extensions

Perform space missions to characterize more precisely quantities and compositions of exogenous and sub-surface organic material.

Construct integrated models of the chemistry on the prebiotic earth that include contributions from different sources of organic matter and environmental constraints.

Perform planetary subsurface missions to obtain virgin endogenous material.

Perform planetary missions to understand possibilities for prebiotic evolution.

Question: How Does Life Begin and Develop?

Origin of Life's Cellular Components

Objective 2: Develop and test plausible pathways by which ancient counterparts of membrane systems, proteins and nucleic acids were synthesized from simpler precursors and assembled into protocells.

For living systems to emerge from abiotic matter, organic constituents on the prebiotic Earth must have self-organized and acquired the capabilities needed to survive and reproduce, thus forming the earliest precursors of life. Eventually, the biomolecules of life became enclosed within a lipid membrane, forming rudimentary assemblages that resembled cells as we know them, or protocells. Among the essential protocellular functions were the acquisition and transduction of energy from the environment, and catalysis to support the synthesis of cellular components (metabolism) and information transfer to succeeding generations (genetics). To explain the origin of life on Earth, it is necessary to demonstrate that essential functions can be accomplished utilizing only the molecules that may have been available in the protobiological milieu. In contemporary life, all these functions are performed by complex systems of proteins, nucleic acids, and membrane-forming material. The early systems must have been much simpler.

Implementation

Near- to Mid-Term

Conduct ground-based laboratory research on chemical pathways leading to the emergence of the macromolecules of life. These pathways should be consistent with the thermodynamic and environmental constraints on the early earth.

Develop models of primitive bioenergetics, replication, and catalysis of the reactions in metabolic pathways which can be linked via plausible, continuous paths to the same functions in modern organisms on earth.

Future Extensions

Combined with studies on the chemistry and environmental conditions on the prebiotic earth and with the analysis of metabolic evolution of microorganisms, this work will ultimately lead to the reconstruction of protobiological evolution from a collection of organic molecules to the earliest, unicellular organisms.

Question: How Does Life Begin and Develop?

Models for Life

Objective 3: Establish replicating, catalytic systems capable of evolution and construct laboratory models of metabolism in primitive living systems.

To the best of our knowledge, the principal attributes of living systems anywhere in the Universe are their capabilities to replicate, to catalyze the chemical reactions of life, to integrate their diverse components to act in concert to support these activities, and to evolve. Building models that exhibit these properties from nucleic acids, proteins, membrane-forming molecules, other organic molecules and possibly minerals, and establishing the range of conditions under which these systems can operate, will provide essential clues about hypothetical, different life forms that may have arisen beyond the Earth. Such new models for the formation of chemical systems with the attributes of life can be predicted by computer simulations and constructed in laboratory experiments.

Implementation

Near- to Mid-Term

Through laboratory experiments, develop and characterize self-replicating systems based on diverse molecules and recognition mechanisms.

Based on in vitro evolution and rational design, construct simple structures capable of catalyzing biochemical reactions, driving bioenergetics and performing other functions of a living system. Demonstrate coupling between these functions.

Develop a computational research program to describe and understand auto-catalytic reaction networks, self-organization and self-reproduction phenomena, and collective behavior of simple biological systems with and without central (genomic) control.

Future Extensions

Construct models of self-replicating, evolving systems, capable of performing the basic functions of a living system. Relate these models to the environmental conditions in habitable zones in which they may arise. Of special interest are conditions that may have existed on Mars and Europa. This could provide clues about extinct or extant life forms, and generic recognizable features, that may be found in missions to these bodies.

Establish the general, physical and chemical principles that drive the emergence of catalytic networks of chemical reactions, self-replication and the formation of cell-like compartments. General models of living systems offer considerable promise for biotechnology.

Question: How Does Life Begin and Develop?

Genomic Clues to Evolution

Objective 4: Expand and interpret the genomic database of a select group of key microorganisms in order to reveal the history and dynamics of evolution.

Modern computational techniques in genomics and bioinformatics give exciting new insights into biological structure and function at all levels. Using these increasingly sophisticated techniques, detailed studies of evolutionary dynamics at the genome level should be conducted, ultimately to allow the reconstruction of the development of genetic complexity through evolutionary relationships. Recognizing that simple mutation and selection are not the sole drivers for evolutionary change, we must define the roles of mechanisms such as gene transfers between organisms, and gene duplication and gene rearrangement within an organism. Using the large array of databases now available, we must extend studies of individual gene families to previously uncharacterized microbial species. These studies, along with phylogenetic studies of evolutionary orthologues for key metabolic and information-processing systems in living cells, comparisons of sequences from discrete evolutionary lineages, and evolutionary studies of complex gene families within a single genome, will help determine when and how key biological functions arose and spread.

Implementation

Near- and mid-term:

Exploit the genomic databases that are already available, studying them in order to infer sequences of evolutionary steps and thus to estimate mechanisms (for example, duplication vs. transfer of genes). Notable progress for eukaryotic organisms can be expected using this approach.

Expand the databases by instituting a program of genomics focused on organisms representative of the metabolic diversity found among the prokaryotes. Full closure, with complete coverage of an organism's genome, is not required. Instead, information highly useful for the goals of the Astrobiology program can be obtained from the techniques of so-called "random genomics," in which accessible fragments resulting from diverse cleavages are sequenced.

Develop new information systems to organize and interpret molecular sequence data in order to determine the mechanisms, frequency, and impact of key molecular drivers of evolution.

Future Extensions

This effort will contribute to a model for the evolutionary dynamics of microbial genomes, with potential applications that range from a reconciliation of biomolecular records of early life with geologic records, and also to enabling revolutionary new vistas in bioengineering.

Question: How Does Life Begin and Develop?

Linking Planetary and Biological Evolution

Objective 5: Describe the sequences of causes and effects associated with the development of Earth's early biosphere and the global environment.

It has already been established in specific instances that the environment has influenced the evolution of certain biota. For example, respiring animals have developed as atmospheric levels of oxygen increased. But the events that have triggered such linked trends and the forces that have sustained them are either unknown or poorly characterized. We can ask, did the geologically controlled availability of a particular trace element suddenly allow the synthesis of a key enzyme? Or, were biological developments themselves the initiators? To answer such questions, we must more accurately determine the times at which biological and geological events occurred, the sequences of the steps involved, and the budgets and distributions of geochemical reactants and products in the Earth's crust, oceans and atmosphere. In this way, we can attach dates and environmental contexts to evolutionary events, and thereby develop a robust, integrated history of the biosphere that incorporates biomolecular, paleoenvironmental, and paleobiological evidence.

Implementation

Near- to Mid-Term

Conduct intensive sampling of ancient sediments to reconstruct, at high temporal resolution, their settings at the times of their deposition.

Examine such comprehensive collections using geochemical and paleontological techniques at levels of detail that allow the dissection of the record of key events in earth history and the definition and testing of plausible relationships between causes and effects.

Elaborate the phylogenies and mechanisms of evolution of key enzymes and of metabolic pathways that had profound impacts on the environment (e. g., production of biomass, oxygenic photosynthesis, sulfate reduction, nitrogen fixation, and methanogenesis).

Define those features within the record (morphological fossils or rock textures, biogeochemical signals) that are related to those significant evolutionary transitions.

Reconstruct the development of the biogeochemical cycles of carbon and of its redox partners.

Because of their clear relevance to planetary exploration, search specifically for strata that provide information about possible forms of life and chemical reactions in hydrothermal systems, aquifers, and evaporitic basins.

Future Extensions

Determine the first appearances of novel organisms and integrate them with molecular phylogenies using quantitative approaches to the fossil record and precise geochronology. A better understanding of the fossil records of extreme environments will greatly improve the effectiveness of the search for life on other worlds. These studies will lead to a better understanding of the evolution of Earth's biosphere and environment.

Develop chronologies on less than 10,000 year timescales to broaden our understanding of ecosystem responses to rapid changes, relevant to human-related timescales.

Question: How Does Life Begin and Develop?

Microbial Ecology

Objective 6: Define how ecophysiological processes structure microbial communities, influence their adaptation and evolution, and affect their detection on other planets.

We must expand studies of microbial ecosystems because the diversification, evolution, and survival of the early biosphere depended upon the efficient coordination of resources and processes by diverse microbial populations. Interdisciplinary studies of microbial communities are required to identify the genetic and environmental factors that influenced the spread of biological diversity and its impact on biospheric change. For example, we must define and quantify the relationship between environmental heterogeneity and microbial diversity and its bearing on evolution. We must understand how organisms affect each other, and how ecosystems modulate the environment through the processes of chemistry and the changing composition of the oceans and atmosphere due to natural geophysical processes and biology.

Implementation

Near- and mid-term

Establish how mutualistic and competitive interactions within communities influence the development of biological diversity.

Document the role of ecological processes in the exchange of genetic information between microorganisms.

Document how microbial communities produce biological marker compounds, structures, minerals, and isotopic compositions that might serve as ecological signatures preserved in rocks and detectible in remotely-sensed atmospheres.

Relate microbial communities to their fossil equivalents by understanding the processes of diagenesis, mineralization and burial of these communities.

Future Extensions

Microbial ecological studies will substantially improve our understanding of early life's adaptation and evolution. These studies will guide the development of both laboratory and theoretical models for the structure and function of ecosystems. These models will contribute ultimately to a better understanding of life's potential to adapt to future changes on Earth and beyond.

Question: Does Life Exist Elsewhere in the Universe?

The Extremes of Life

Objective 7: Identify the environmental limits for life by examining biological adaptations to extremes in environmental conditions.

The habitable zone is defined ultimately by life's capacity to adapt to extremes in key environmental parameters. For example, Mars' habitability is severely constrained by low temperatures, low water potential, and damaging photochemical reactions. The hazards of extreme conditions can be mitigated by biochemical and structural countermeasures within cells, and by processes at the ecosystem level. An effective research program will combine studies of natural ecosystems, physiology, and genetics with the development of new research technologies and missions for the exploration of extreme environments--first in our own Solar System and later, beyond.

Implementation

Near- to Mid-Term

Identify and characterize the biota in those extreme environments on Earth that are most relevant for a search for life on Mars and Europa.

Define more completely the range of strategies for obtaining biochemically-useful energy.

Define the mechanisms that cells and ecosystems have evolved to survive the extremes in environmental conditions.

Define the potential for fossilization and preservation of biota in extreme environments.

Determine whether the life forms from extreme environments on Earth could exist in other planetary environments.

Future Extensions

This research will help to define more completely the full range of life's capacities for survival. It will lead to more effective strategies to search for life beyond Earth, because it will aid in the selection of sites for exploration, and it will optimize our ability to recognize evidence of life and its fossils.

Question: Does Life Exist Elsewhere in the Universe?

Past and Present Life on Mars

Objective 8: Search for evidence of ancient climates, extinct life and potential habitats for extant life on Mars.

The requirements for life on Earth imply that liquid water is the critical requirement for life on other worlds of the Solar System. Operationally, the search for past or present life is therefore a search for past or present environments where liquid water may be (or may have been) found. There is direct evidence that Mars once had liquid water on its surface, and indirect evidence that even today there may be subsurface Martian aquifers and/or hydrothermal systems. The search for fossils -- either biochemical or structural- would focus on aquatic depositional environments, such as sedimentary deposits from former lakes or hydrothermal systems. Chemical analyses of samples formed under habitable conditions can offer insights into biologically-relevant chemistry that may have occurred in these environments. Both the selection of sites bearing evidence of habitable environments (past and present) and the in-situ analysis of surface materials will enable a sample return program that effectively addresses astrobiology goals.

Implementation

Near- to Mid-Term

Continue to collect martian meteorites and conduct comprehensive analyses of them. Improve methodologies for identifying biomarkers.

Conduct global visual and spectral reconnaissance of Mars to identify paleolakes and sites of past hydrothermal activity by determining the presence of fluvial features, shorelines, and precipitates such as carbonates, phosphates, silica and evaporites.

Locate, sample and characterize geologic deposits that record evidence of the early Mars climate and potential biosphere.

Develop geophysical methods to remotely characterize the potential for subsurface liquid water on Mars. Working with external agencies and industry, develop technologies capable of accessing and retrieving samples from deep (>5km) below the martian surface.

Develop technologies for accessing broad areas of the Martian surface.

Implementation

Future Extensions

On Mars access to sediments deposited in lakes as well as potential subsurface hydrospheres requires sampling capabilities beyond the current state-of-the-art. To reach paleolake sediments it would be necessary to get through the aeolian dust which may extend to depths of 10 meters, and access to depths of 5 or more kilometers may be required for hydrospheres. The long terms goals in the search for extant and extinct life on Mars thus rely in large extent upon broadening the sphere of Martian exploration through advanced mobility and drilling technologies. Even in the short term, greater access will allow sample returns with greater relevance to life. These returned samples will help us look more effectively for life elsewhere. In the long term, increasing the sphere of exploration will set the stage for the human assisted search for past or present life on Mars.

Question: Does Life Exist Elsewhere in the Universe?

Life's Precursors and Habitats in the Outer Solar System

Objective 9: Determine the presence of life's chemical precursors and potential habitats for life in the outer solar system.

Recent tantalizing evidence for the possible presence of subsurface liquid water on Europa and other Solar System bodies has extended the search space for life to the outer Solar System. A first step in this search, as with Mars exploration, is to determine the spatial and temporal distribution of liquid water in our Solar System. The discovery of organic or other prebiotic substances on these bodies may shed light on both the origin of these materials and the chemical processes that determine(d) their composition. For example, we might establish whether prebiotic substances came from the infall of primitive exogenous debris, or from aqueous chemical transformations within Europa itself. This knowledge will help us understand the relevance of such chemistry to prebiotic processes and/or life itself, either Earth-based or extraterrestrial. Finally, observations of Titan -- and lesser bodies such as comets and asteroids -- will shed light on the complexity and prebiotic relevance of organic chemical reactions that occurred in those bodies.

Implementation

Near- to Mid-Term

Determine the organic and biogenic element composition of the gas, ice particles, dust and smaller bodies (eg. comets and asteroids).

Develop orbital flight experiments to determine the inventory of organic compounds and biogenic elements on Europa's surface.

Map the thickness of the surface ice and search for evidence of liquid water on Europa.

Initiate technology development for in-situ and/or sample return analysis of surface material on Europa associated with dark (linear, etc.) surface features.

Future Extensions

Explore further for evidence of habitable conditions and/or life on Europa and other outer planet satellites. Analyze, in situ and on returned samples, organic material from the youngest units on Europa for biogenic origin. Initiate technology development for exploration of the purported subsurface ocean on Europa, searching for signs of life.

Develop technology for performing chemical analyses of comets, asteroids and other small objects to determine their prebiotic relevance.

Question: Does Life Exist Elsewhere in the Universe?

Natural Migration of Life

Objective 10: Understand the natural processes by which life can migrate from one world to another.

The observational data that demonstrates the availability of organic molecules and water throughout the cosmos raises the possibility that living systems can exist beyond Earth. Other data allow us to argue that life could be transported between planetary bodies and could, possibly, become established on another world. Current models indicate that there are natural means to propel organisms into interplanetary space. For example, meteorites that originated on Mars have been found on Earth; these samples verify that such an exchange of planetary material has occurred. In addition, experimental evidence from the orbiting Long Duration Exposure Facility and from at least one Surveyor lunar lander indicates that some common terrestrial microorganisms can survive in excess of five years. Finding life in extreme environments on Earth suggests that life might survive in liquid water niches on other planetary surfaces, and that certain life forms may be common throughout our Solar System. For several reasons pertinent to astrobiology, we must determine if life from one world can establish an evolutionary trajectory on another.

Implementation

Near- to Mid-Term

Establish models to determine probabilities for life's transport to, and survival on another planet.

Search for evidence of an external origin for terrestrial life, or of exchanges between the biosphere of Earth and of that Mars or other planets. Search for this evidence in meteorites, in geologic samples and in the biochemistry of life.

Sample and analyze cometary material to search for evidence of extraterrestrial life or its precursors. Examine meteor storms, comet coronae and tails, and cometary debris collected by orbiting satellites.

Future Extensions

The potential seeding of Earth life on other planetary surfaces, both intentionally and unintentionally, is possible.

Understand the interplanetary transportation and survivability of organisms and use this information as a basis for quarantine of samples returned to Earth

Question: Does Life Exist Elsewhere in the Universe?

Origin of Habitable Planets

Objective 11: Determine (theoretically and empirically) the ultimate outcome of the planet-forming process around other stars, especially the habitable ones.

Because of our working assumption that life is a planetary phenomenon, we must understand the planet formation process. Astronomers must determine, in a statistically valid manner, the distribution of planets and planetary orbits and masses -- around a range of star types having a range of ages. Specifically, astrobiology is most concerned with habitable planets, defined as those where liquid water can exist on the surface. Other types of bodies, for example Saturn's moon, Europa, might have subsurface liquid water and perhaps subsurface life as well, but the life zones on such bodies cannot be examined remotely in the way that surface biospheres can. The size and location of this zone varies with the type of star and its age. A multi-pronged program should be mounted to detect habitable planets in sufficient numbers so as to understand their distribution, and help guide the development of future large spaceborne interferometers -- the technique of choice for finding (and, perhaps, characterizing) distant planetary bodies.

Astrobiologists must also create theoretical models of the processes that lead to the origins of habitable planets, to understand the provenance of the water, minerals, and organics that permit the origin and early evolution of life. Analyses of meteorites will continue to help us constrain these models.

Implementation

Near- to Mid-Term

Conduct theoretical modeling of the planetary formation process, and catalog the conditions that lead to habitable planets. Incorporate meteoritical studies of aqueous alteration of primitive bodies as in-situ boundary conditions on these models.

Conduct ground based studies to search for the smallest planets that can be detected around a variety of stellar types. Utilize a variety of techniques, including astrometry (Keck and Large Binocular Telescope interferometers, plus others), radial velocity searches, and eclipse photometry, to carry out sustained searches for habitable planets. This will lead to solutions for key technological, and data analysis problems facing larger spaceborne systems.

Carry out eclipse photometry or alternative techniques that will characterize the distribution, sizes, and orbits, of planets surrounding a wide variety of star types, with adequate statistics to establish the properties of the planet forming process, down to and including terrestrial size planets in the habitable zones of their stars.

Coordinate efforts with existing and planned facilities to study the process of planetary system formation: SIRTF and SOFIA to inventory the number and composition of small bodies in the Solar System, and to study protoplanetary disks in the Galaxy; SIM to accurately characterize the dynamics of planetary systems identified by the survey mission. o Simulate in the laboratory the formation, growth, and evolution of interplanetary grains and organics that contribute directly to planet formation.

Develop the criteria for, and a catalog of potentially habitable systems.

Future Extensions

Construct coupled cosmochemical/astrophysical evolution models of growing planetesimals and early planets that can serve as boundary conditions for the origin of life. This will lead to understanding aspects such as the influence of early core formation and metal segregation, and giant impacts (as perhaps controlled by different configurations of giant planets) on thermal, oxidation, and atmospheric state.

Contribute these research findings to the development and flight of TPF to image nearby planetary systems and take global spectra of planets in the habitable zones.

Question: Does Life Exist Elsewhere in the Universe?

Effects of Climate and Geology on Habitability

Objective 12: Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help define the frequency of habitable planets in the universe.

The limits of a star system's habitable zone are determined in part by the stability of liquid water on the surface of planetary bodies, both instantaneously and over long time periods, as the parent star luminosity changes. Planetary habitability also depends on the stability of the planetary system, including the gravitational effects of large (Jovian-sized) planets or nearby stars on the distribution and dynamics of potential large impactors. Detection of habitable planets outside of our own Solar System will rely on spectroscopic observation of key atmospheric constituents--including water, carbon dioxide, ozone, and possibly others. Among the factors which affect liquid water's stability are the mass, composition, and dynamics (including effects of clouds) of a planet's atmosphere. The development of multidimensional general atmospheric circulation models--including the effects of clouds--for other planets will be critical in defining the distribution of liquid water in the universe.

Implementation

Near- to Mid-Term

Conduct a theoretical research program to model the role of clouds (both CO_2 and H_2O) on early Mars, to explore cloud formation, radiative effects, and effects on atmospheric dynamics, all of which affect the location of the outer edge of the liquid water region, or habitable zone.

Study the radiative effect of water clouds in a dense, runaway greenhouse atmosphere such as may have existed on Venus, and determine how this influences the location of the inner edge of the habitable zone.

Extend these models to include a broader range of planetary sizes and orbital radii, in order to explore more fully the role of climate in determining the extent of habitable zones in other putative solar systems.

Search for direct, in situ evidence for liquid water on Mars, along with other surface minerals (e.g., carbonates and sulfates) that may provide information about long-term climate evolution.

Develop better models of how hydrogen escapes from H_2-rich, primitive atmospheres and how this would have affected atmospheric evolution on the early earth and on other, Earth-like planets.

Determine whether the primitive Earth (and, by extension, other planets) could have developed an organic-rich, atmospheric haze layer such as that found on Titan, and explore the consequences of such haze layers for atmospheric and biological evolution.

Future Extensions

These models ultimately will generate a paradigm for planetary habitability to help guide, as well as be tested by, astronomical observations of extrasolar habitable planets. The interplay between these climate models and the Mars sample return analysis program will allow us to determine whether Mars is inhabited now or whether it may have been inhabited in the past.

Question: Does Life Exist Elsewhere in the Universe?

Extrasolar Biomarkers

Objective 13: Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extrasolar planet.

Perhaps within the next decade or so, we will be able to obtain infrared spectra of extrasolar planets that are situated within the habitable zones of stars within approximately 15 parsecs (approximately 50 light years) of our own Solar System. Accordingly, we must develop the database for interpreting those spectra, both for evidence of habitable conditions (e.g., the presence of liquid water) and for evidence of life. Aspects of the strategy include developing appropriate observational approaches that optimize sensitivity and spectral and spatial resolution, creating models of atmospheric chemistry and its evolution, and achieving an understanding of the factors that control the composition of biological gas emissions to the atmosphere. We must develop the ability to discriminate between those environmental conditions and gas compositions that indicate a geologically active but "lifeless" planet, versus those conditions and compositions that compel a biological interpretation.

Implementation

Near- to Mid-Term

Determine the atmospheric compositions that are maintained during the lifetimes of habitable planets that lack biospheres.

Define the biological and environmental controls upon the emission of biogenic gases, including oxygen, to the atmosphere.

Develop global models for the composition of Earth's early atmosphere, with particular emphasis upon the fate of reduced biogenic gases. Calculate synthetic spectra of Earth-like planetary atmospheres, both with and without free O_2, to aid in designing future space-based interferometry missions, such as TPF.

Identify a menu of biologically-produced volatile atmospheric species that could be detected using an interferometric telescope having a resolving power (l/Dl) of 100.

Define the spectral signatures of the earth's surface that might be detected remotely and provide evidence of life.

Future Extensions

The requirements for detecting extrasolar biospheres in association with a range of atmospheric compositions will be key drivers behind the designs of interferometric telescopes that will obtain spectra of extrasolar planets. The astrobiology research program therefore must contribute substantially to the optimization of those designs. The program must lead the continuing search for novel methods to detect remote biospheres spectroscopically.

Question: What is Life's Future on Earth and Beyond?

Ecosystem Response to Rapid Environmental Change

Objective 14: Determine the resilience of local and global ecosystems through their response to natural and human-induced disturbances.

The ability of a planet to support the long-term existence of life depends upon life's ability to withstand changes in its environment from a variety of causes. Throughout its history, life on Earth has experienced such changes with events ranging from impacts of asteroids and comets-- and their resultant global manifestations -- to ice ages of varying duration. Throughout each of these changes, life generally has responded initially with reductions in genetic diversity, followed by recoveries and continued increases in biodiversity. The current possibilities for major impact of human activities on the terrestrial biosphere (such as the depletion of stratospheric ozone) constitute an excellent observational laboratory to test the vulnerability of ecosystems, both large and small, to environmental changes with timescales commensurate with those of human culture. Studies of such ecosystem response to rapid environmental changes will help extend ecosystem models on the Earth and to other worlds, allow predictions of responses to major, planet-wide changes, and identify limits to these changes beyond which life may not be able to recover.

Implementation

Near- to Mid-Term

Determine the critical biophysical and geochemical components and process interactions during the reformation of terrestrial ecosystems, by conducting field campaigns to sites where recent near-sterilizing events have destroyed most of a natural ecosystem (e.g., areas near volcanic eruptions, burn scars from major wildfires, oil spill sites, etc.). Couple species recovery patterns with selected measurements of radiation balance, microclimate, toxicity and biogeochemistry.

Determine key spectral indicators of life's response to major environmental changes such as air and water temperature changes, volcanic eruptions, pollution, deforestation, desertification, etc.

Create local and global models of increasing complexity, of ecosystems and their response to changes in the environment.

Support technology development of advanced spectroscopic sensors (particularly hyperspectral), automation and information processing suited for obtaining key data on entire ecosystems and their environments.

Future Extensions

Extend ecosystem perturbation models to increasingly large sizes, eventually aiming for global predictive models. Include remotely-sensed data, coupled with ground truth measurements, to refine these models.

Apply models obtained through research on ecosystem response to the development of biomarkers for remote detection of life.

Develop models of ecosystem change that ultimately could assist our understanding of change in the geologic past.

Question: What is Life's Future on Earth and Beyond?

Earth's Future Habitability

Objective 15: Model the future habitability of Earth by examining the interactions between the biosphere and the chemistry and radiation balance of the atmosphere.

Life on Earth has been so successful that the very environmental conditions needed to support present-day life forms are strongly coupled to -- and modified by -- ecological processes. The chemistry of Earth's atmosphere is strongly influenced by life. For example, the evolution of oxygenic photosynthesis ultimately led to an oxygen-rich atmosphere and to the development of the protective ozone layer to block lethal fluxes of ultraviolet radiation. The production and consumption of radiatively-active trace gases -- which influence global temperatures--are mediated by microbial and plant ecosystems. In the near-future, human-induced changes in levels of carbon dioxide and trace gases will alter the radiation balance of the atmosphere. In the more distant future, long-terms trends in biogeochemical cycling and solar luminosity will drive environmental changes that will compel the biosphere to adapt. Therefore, the environmental conditions of a habitable planet are influenced, not only by external and geological factors, but also by the biosphere, including humanity, and how it has evolved.

Implementation

Near- to Mid-Term

Define, through both remote sensing analysis using the Earth Observing System and aircraft, as well as new laboratory and field ecology experiments, aspects of the chemistry of Earth's atmosphere that are strongly dependent on ecological processes and biogenic trace gas fluxes.

Develop new observations of the oceans and terrestrial surface that can be incorporated into coupled models of global atmospheric chemistry, and to the extent possible, used to hindcast into the past for calibration and to predict into the future.

Develop models of Earth's historical biogeochemistry, and combine these with retrospective experimental studies to understand the geochemical relations of ecosystems and organism-level studies of physiological capacity.

Future Extensions

Use computer modeling and remote sensing data analysis to develop new theories of the potential non-linear responses that can be expected in coupled biosphere-atmosphere systems. Support the coupling of Atmospheric General Circulation Models (AGCMs) with paleo-ecological observations and modern satellite perspectives of the Earth's changing biosphere.

Question: What is Life's Future on Earth and Beyond?

Bringing Life with Us beyond Earth

Objective 16: Understand the human-directed processes by which life can migrate from one world to another.

For the first time in human history, we can intentionally move life beyond our home planet. As a result, humanity is entering a new evolutionary territory -- space -- in a manner analogous to the first sea creature crawling out onto the land, with the attendant requirement for supporting technology. This time, however, we are able to document this evolutionary trajectory with the tools of modern molecular biology and to engineer artificial ecologies that may be necessary for evolutionary success in this new environment. Two factors must converge to enable the successful evolution of terrestrial life beyond Earth. First, we must understand and provide the physiological requirements for reproduction in space for a wide range of organisms. Second, we must engineer the artificial ecosystems that would promote survival and evolutionary success beyond Earth. The results derived from addressing this objective will answer a fundamental question about life in the universe generally and the nature of life on Earth specifically. Is life purely a planetary phenomenon or is life able to expand its evolutionary trajectory beyond its home planet?

Implementation

Near- to Mid-Term

Use low earth orbit opportunities as a testbed for studying evolution and ecological interactions in the space environment (microgravity and/or high radiation) of organisms from simple to complex, including "wild" biota indigenous to the spacecraft, and determine how to promote evolutionary success. Extend these investigations to other planetary bodies in concert with human exploration of the solar system.

Identify adaptive mechanisms for responses to changes in gravity, radiation, pressure, temperature, and atmospheric components on a variety of organisms and ecosystems; identify the biological responses of these organisms and ecosystems to the space station environment or the environment on other planets.

Establish environmental limits for terrestrial life, especially those that have the potential to survive without protection or with minimal protection on other worlds.

Elucidate the characteristics of environments necessary to sustain life in space and beyond including higher plants and animals as part of a sustained regenerative ecology and indigenous resources in extraterrestrial environments.

Conduct multiple generation studies of multicellular organisms on the Space Station to determine if complex life can evolve beyond Earth.

Engineer closed and open environments as prototypes for human exploration of other planets. Test such system in analog environments on Earth and in space.

Future Extensions

Place candidate ecosystems on extraterrestrial surfaces and document their evolution.

Establish permanent colonies of humans and other organisms in space and on another planetary surface.

Engineer life for survival, adaptation, and evolution beyond Earth.

Question: What is Life's Future on Earth and Beyond?

Planetary Protection

Objective 17: Refine planetary protection guidelines and develop protection technology for human and robotic missions.

Within the coming decade, significant advances in astrobiology are likely to come from from many sources -- remote sensing, in situ experiments, sample return missions, and Earth based research. We can anticipate that this new information about physical, chemical and geological environments on planets, planetary satellites, and other Solar System bodies will provide important details related to the origin, evolution, nature, and evolutionary potential for living entities on Earth and elsewhere. During this period of intense exploration and research, there will be a continuing need to apply planetary protection principles to avoid scientifically and biospherically harmful cross contamination of the planets and celestial bodies. Such planetary protection controls must meet NASA and COSPAR policies, satisfy technical and scientific concerns, and reassure the public that appropriate safeguards will be taken at every step of exploration.

Implementation

Near- to Mid-Term

Conduct an international conference to discuss the ethical issues associated with planetary protection.

Assess the risk and potential impact of importation of alien life to a planet.

Develop the knowledge base and recommendations for implementation plans and policies for human exploration.

Review and recommend refinements to planetary protection policies and guidelines for robotic solar system exploration that incorporate the latest scientific information and technological advances.

Enlist the aid of a broad contingent of international experts to explore ethical and theological questions related to the existence of extraterrestrial life, the potential for harmful cross contamination, and the implications of long-term, large-scale space and planetary exploration, habitation and engineering.

Develop methodologies, taking advantage of the latest technologies, to aid in the implementation of planetary protection for robotic missions. These will include containment and isolation on Earth, life detection, cleaning and sterilization.

Future Extensions

Understand the risk for cross-contamination of life throughout the solar system.

Develop new or refined technologies necessary to avoid harmful cross contamination during human exploration.

Develop and deploy new technologies to sense life and its diversity, to guide our exploration of the universe.

Principles

In addition to goals and objectives, the NASA Roadmap emphasizes four operating principles that are integral to the Astrobiology Program.

Principle 1: Astrobiology is multidisciplinary, and achieving our goals will require the cooperation of different scientific disciplines and programs.

Principle 2: Astrobiology encourages planetary stewardship, through an emphasis on protection against biological contamination and recognition of the ethical issues surrounding the export of terrestrial life beyond Earth.

Principle 3: Astrobiology recognizes a broad societal interest in our subject, especially in areas such as the search for extraterrestrial life and the potential to engineer new life forms adapted to live on other worlds.

Principle 4: In view of the intrinsic excitement and wide public interest in our subject, Astrobiology includes a strong element of education and public outreach.